HOMOGENEITY OF THE PURE STATE SPACE OF THE CUNTZ ALGEBRA

OLA BRATTELI AND AKITAKA KISHIMOTO

ABSTRACT. If ω_1, ω_2 are two pure gauge-invariant states of the Cuntz algebra $\mathcal{O}_d$, we show that there is an automorphism α of $\mathcal{O}_d$ such that $\omega_1 = \omega_2 \circ \alpha$. If ω is a general pure state on $\mathcal{O}_d$ and φ_0 is a given Cuntz state, we show that there exists an endomorphism α of $\mathcal{O}_d$ such that $\varphi_0 = \omega \circ \alpha$

1. INTRODUCTION

Let $\mathfrak{A}$ be a simple separable C*-algebra, and let π_1, π_2 be representations of $\mathfrak{A}$ on Hilbert spaces $\mathcal{H}_1, \mathcal{H}_2$. The representations π_1, π_2 are said to be algebraically equivalent if $\pi_1(\mathfrak{A})''$ and $\pi_2(\mathfrak{A})''$ are isomorphic von Neumann algebras. If there is an automorphism α of $\mathfrak{A}$ such that π_1 and $\pi_2 \circ \alpha$ are quasi-equivalent, then π_1, π_2 are clearly algebraically equivalent. Powers proved in [Pow67] that if $\mathfrak{A}$ is a UHF algebra the converse is true. His method extends readily to the case that $\mathfrak{A}$ is an AF-algebra, [Bra72]. See also section 12.3 in [KR86]. In the special case that π_1 (and therefore π_2) is irreducible, Kadison's transitivity theorem therefore implies that if $\mathfrak{A}$ is a simple AF algebra and if ω_1 and ω_2 are pure states on $\mathfrak{A}$, there exists an automorphism α of $\mathfrak{A}$ such that $\omega_1 = \omega_2 \circ \alpha$. To our knowledge, this question has only been settled in the affirmative when $\mathfrak{A}$ is an AF-algebra. As a beginning of a possible resolution of the question for purely infinite algebras, we here prove the statements in the abstract. Recall from [Cun77] that the Cuntz algebra $\mathcal{O}_d$ is the C*-algebra generated by d operators $s_1, \dots, s_d$ satisfying

$$s_j^* s_i = \delta_{ij} \mathbb{1}$$
$$\sum_{i=1}^{d} s_i s_i^* = \mathbb{1}$$

There is an action γ of the group $U(d)$ of unitary $d \times d$ matrices on $\mathcal{O}_d$ given by

$$\gamma_g(s_i) = \sum_{j=1}^{d} g_{ji} s_j$$

for $g = [g_{ij}]_{i,j=1}^d$ in $U(d)$. In particular the *gauge action* $\tau = \gamma|_{\mathbf{T}}$ is defined by

$$\tau_z(s_i) = z s_i \ , \qquad z \in \mathbf{T} \subset \mathbf{C} \ .$$

If UHF_d is the fixed point subalgebra under the gauge action, then UHF_d is the closure of the linear span of all Wick ordered polynomials of the form

$$s_{i_1} \dots s_{i_k} s_{j_k}^* \dots s_{j_1}^*$$

UHF_d is isomorphic to the UHF algebra of Glimm type d^∞:

$$\mathrm{UHF}_d \cong M_{d^\infty} = \bigotimes_1^\infty M_d$$

in such a way that the isomorphism carries the Wick ordered polynomial above into the matrix element

$$e^{(1)}_{i_1 j_1} \otimes e^{(2)}_{i_2 j_2} \otimes \cdots \otimes e^{(k)}_{i_k j_k} \otimes \mathbb{1} \otimes \mathbb{1} \otimes \cdots .$$

The gauge action τ is in fact characterized by the fact that its fixed point algebra is isomorphic to UHF_d, i.e. if α is another faithful action of $\mathbf{T}$ on $\mathcal{O}_d$ such that the fixed point algebra $\mathcal{O}_d^\alpha$ is isomorphic to UHF_d, then either $z \mapsto \alpha_z$ or $z \mapsto \alpha_z^{-1}$ is conjugate to τ. This follows from [BK99, Corollary 4.1]. (Since UHF_d is simple and α is faithful, the crossed product $\mathcal{O}_d \times_\alpha \mathbf{T}$ is stably isomorphic to UHF_d, [KT78], and in particular it is simple. Since

$$\mathcal{O}_d^\alpha \cong P_\alpha(0)(\mathcal{O}_d \times_\alpha \mathbf{T})P_\alpha(0) ,$$

$[P_\alpha(0)]$ is just $[\mathbb{1}]$ when $K_0(\mathcal{O}_d \times_\alpha \mathbf{T})$ is identified with $K_0(\mathcal{O}_d^\alpha)$. By the Pimsner-Voiculescu exact sequence it follows that $\widehat{\alpha}_*$ on $K_0(\mathcal{O}_d \times_\alpha \mathbf{T}) = \mathbf{Z}[\frac{1}{d}]$ is multiplication by d or $1/d$.) Because of this, our main result Theorem 5 can be given the following more universal form:

Corollary 1. *Let φ_1 and φ_2 be pure states on $\mathcal{O}_d$, and assume that there exist actions α_i of $\mathbf{T}$ on $\mathcal{O}_d$ such that $\mathcal{O}_d^{\alpha_i} \cong \mathrm{UHF}_d$ and $\varphi_i \circ \alpha_i = \varphi_i$ for $i = 1, 2$. Then there exists an automorphism β of $\mathcal{O}_d$ such that*

$$\varphi_1 = \varphi_2 \circ \beta$$

The question whether any pure state on $\mathcal{O}_d$ is invariant under a gauge action like this is left open.

The restriction of γ_g to UHF_d is carried into the action

$$\mathrm{Ad}(g) \otimes \mathrm{Ad}(g) \otimes \cdots$$

on $\bigotimes_1^\infty M_d$. We define the canonical endomorphism λ on UHF_d (or on $\mathcal{O}_d$) by

$$\lambda(x) = \sum_{j=1}^d s_j x s_j^*$$

and the isomorphism carries λ over into the one-sided shift

$$x_1 \otimes x_2 \otimes x_3 \otimes \cdots \to \mathbb{1} \otimes x_1 \otimes x_2 \otimes \cdots$$

on $\bigotimes_1^\infty M_d$.

If $\eta_1, \dots, \eta_d$ are complex scalars with $\sum_{j=1}^d |\eta_j|^2 = 1$, we can define a state on $\mathcal{O}_d$ by

$$\varphi_\eta(s_{i_1} \dots s_{i_k} s_{j_\ell}^* \dots s_{j_1}^*) = \eta_{i_1} \dots \eta_{i_k} \overline{\eta_{j_\ell}} \dots \overline{\eta_{j_1}}$$

[Cun77], [Eva80], [BJP96], [BJ97], [BJKW].

This state is pure, and non-gauge invariant, and the $U(d)$ action is transitive on these states, which are called Cuntz states. The restriction of φ_η to UHF_d identifies with the pure product state given by infinitely many copies of the vector state defined by the vector $(\eta_1, \dots, \eta_d)$ on M_d.

In this paper we will also consider the one-one correspondence between the set $\mathcal{U}(\mathcal{O}_d)$ of unitaries in $\mathcal{O}_d$ and the set $\mathrm{End}(\mathcal{O}_d)$ of unital endomorphisms of $\mathcal{O}_d$. If $u \in \mathcal{U}(\mathcal{O}_d)$ then $\alpha_u(s_i) = us_i$ defines an endomorphism, and if $\alpha \in \mathrm{End}(\mathcal{O}_d)$ the corresponding unitary is $u = \sum_{i=1}^{d} \alpha(s_i)s_i^*$. It has been proved by Rørdam that

$$\mathcal{U}_i = \{u \in \mathcal{U}(\mathcal{O}_d) | \alpha_u \text{ is an inner automorphism}\}$$

is a dense subset of $\mathcal{U}(\mathcal{O}_d)$, [Rør93]. We give a shorter proof of this, and also show that

$$\mathcal{U}_a = \{u \in \mathcal{U}(\mathcal{O}_d) | \alpha_u \text{ is an automorphism}\}$$

is a dense G_δ subset of $\mathcal{U}(\mathcal{O}_d)$ such that the complement $\mathcal{U}(\mathcal{O}_d) \setminus \mathcal{U}_a$ is also dense.

By using the above correspondence between $\mathcal{U}(\mathcal{O}_d)$ and $\mathrm{End}(\mathcal{O}_d)$, it follows (see the proof of Proposition 8) that if ω is a pure state and φ_0 a Cuntz state there exists an endomorphism α of $\mathcal{O}_d$ such that $\varphi_0 = \omega \circ \alpha$. Although the automorphism group is dense in $\mathrm{End}(\mathcal{O}_d)$ (in the topology of pointwise convergence), the question whether α can be chosen to be an automorphism is left open (in this approach).

2. Transitivity of the automorphism group on the pure gauge-invariant states

In this section we prove the first main result mentioned in the abstract.

Let UHF_d be the UHF algebra of type d^∞ and let (A_n) be an increasing sequence of C*-subalgebras of UHF_d such that $\mathrm{UHF}_d = \overline{\cup A_n}$ and $A_n \cong M_{d^n}$. We first use Power's transitivity on UHF_d to find an approximate factorization for any pure state on UHF_d:

Lemma 2. *Let φ be a pure state of UHF_d and $\varepsilon > 0$. Then there exists a pure state φ' of UHF_d, an increasing sequence $\{B_n\}$ of finite type I subfactors of UHF_d, and an increasing subsequence $\{k_n\}$ in $\mathbf{N}$ such that $\varphi' | B_n$ is a pure state of B_n and $A_{k_n} \subset B_n \subset A_{k_{n+1}}$ for every n, and*

$$\|\varphi - \varphi'\| < \varepsilon \, .$$

Proof. Since the automorphism group $\mathrm{Aut}(\mathrm{UHF}_d)$ of UHF_d acts transitively on the set of pure states of UHF_d, [Pow67], there exists an increasing sequence $\{D_n\}$ of finite type I subfactors of UHF_d such that $D_n \cong M_{d^n}$ and $\varphi | D_n$ is pure for every n. Then we can find sequences $\{u_n\}$ and $\{v_n\}$ of unitaries in UHF_d and increasing sequences $\{k_n\}$ and $\{\ell_n\}$ in $\mathbf{N}$ such that

$$\begin{aligned}
&A_{k_1} \subset \mathrm{Ad}(v_1u_1)(D_{\ell_1}) \subset A_{k_2} \subset \mathrm{Ad}(v_2u_2v_1u_1)(D_{\ell_2}) \subset A_{k_3} \subset \cdots \\
&u_n \in \mathrm{UHF}_d \cap \mathrm{Ad}(v_{n-1}u_{n-1} \dots v_1u_1)(D_{\ell_{n-1}})' \\
&v_n \in \mathrm{UHF}_d \cap A'_{k_n} \\
&\|u_n - 1\| < \varepsilon/2^{n+2} \qquad \|v_n - 1\| < \varepsilon/2^{n+2}
\end{aligned}$$

where $D_0 = \mathbf{C}1$. (Let $k_1 = 1$. Then we choose u_1 and ℓ_1 such that $A_{k_1} \subset \mathrm{Ad}\, u_1(D_{\ell_1})$ and $\|u_1 - 1\| < \varepsilon/8$. Further we choose k_2 and v_1 such that $v_1 \in \mathrm{UHF}_d \cap A'_{k_1}$, $\|v_1 - 1\| < \varepsilon/8$, and, $\mathrm{Ad}(v_1u_1)(D_{\ell_1}) \subset A_{k_2}$. We just repeat this process.) Then the limit $w = \lim v_nu_n \dots v_1u_1$ exists and is a unitary such that $\|w - 1\| < \varepsilon/2$ and

$$A_{k_1} \subset \mathrm{Ad}\, w(D_{\ell_1}) \subset A_{k_2} \subset \mathrm{Ad}\, w(D_{\ell_2}) \subset \cdots$$

Let $\varphi' = \varphi \circ \operatorname{Ad} w^*$. Then φ' is a pure state with $\|\varphi - \varphi'\| < \varepsilon$ and $\varphi' | \operatorname{Ad} w(D_{\ell_n})$ is a pure state for every n. Put $B_n = \operatorname{Ad} w(D_{\ell_n})$. ☐

We next show that for any pair of pure states φ_1, φ_2 on UHF_d, there is a tensor product decomposition of UHF_d such that φ_1, φ_2 have approximate factorizations with respect to certain sub-decompositions (necessarily different for φ_1 and φ_2):

Lemma 3. *Let φ_1 and φ_2 be pure states of UHF_d and let $\varepsilon > 0$. Then there exist pure states φ'_1, φ'_2, and ψ of UHF_d, an increasing sequence $\{k_n\}$ in $\mathbf{N}$ and an increasing sequence $\{B_n\}$ of finite type I subfactors of A such that*

$$\begin{aligned}
&\|\varphi_i - \varphi'_i\| < \varepsilon \\
&\varphi'_1 | B_{2n+1} \quad \textit{is pure} \\
&\varphi'_2 | B_{2n} \quad \textit{is pure} \\
&\psi | B_{6k-1} \cap B'_{6k-3} = \varphi'_1 | B_{6k-1} \cap B'_{6k-3} \\
&\psi | B_{6k+2} \cap B'_{6k} = \varphi'_2 | B_{6k+2} \cap B'_{6k} \\
&\psi | B_{6k} \cap B'_{6k-1} \quad \textit{is pure,} \\
&\psi | B_{6k-3} \cap B'_{6k-4} \quad \textit{is pure,} \\
&k_{n+1} - k_n \to \infty \\
&A_{k_1} \subset B_1 \subset A_{k_2} \subset B_2 \subset A_{k_3} \subset B_3 \subset \cdots
\end{aligned}$$

Proof. It follows from the previous lemma that there exist pure states φ'_i, increasing sequences $\{B_{in}\}$ of finite type I subfactors of A, and an increasing sequence $\{k_n\}$ in $\mathbf{N}$ such that

$$\begin{aligned}
&\|\varphi_i - \varphi'_i\| < \varepsilon \ , \\
&\varphi_i | B_{in} \quad \text{is pure for } i = 1, 2 \ , \\
&A_{k_1} \subset B_{i1} \subset A_{k_2} \subset B_{i2} \subset A_{k_3} \subset \cdots
\end{aligned}$$

By passing to subsequences of $\{k_n\}$ and $\{B_{in}\}$ and setting $B_n = B_{1n}$ if n is odd and $B_n = B_{2n}$ if n is even, we may assume that

$$\begin{aligned}
&\varphi'_1 | B_{2n+1} \quad \text{is pure} \\
&\varphi'_2 | B_{2n} \quad \text{is pure} \\
&k_{n+1} - k_n \to \infty \\
&A_{k_1} \subset B_1 \subset A_{k_2} \subset B_2 \subset A_{k_3} \subset \cdots
\end{aligned}$$

Then φ'_1 has a tensor product decomposition into pure states on the matrix subalgebras $B_{2n+1} \cap B'_{2n-1}$, and φ'_2 likewise on the subalgebras $B_{2n} \cap B'_{2n-2}$. Thus we can define a pure state ψ by requiring that it decomposes under the tensor product decomposition

$$\begin{aligned}
\ldots \otimes (B_{6k-4} \cap B'_{6k-6}) \otimes (B_{6k-3} \cap B'_{6k-4}) \otimes (B_{6k-1} \cap B'_{6k-3}) \\
\otimes (B_{6k} \cap B'_{6k-1}) \otimes (B_{6k+2} \cap B'_{6k}) \otimes \cdots
\end{aligned}$$

into states given by:

$$\begin{aligned}
&\psi|B_{6k-1}\cap B'_{6k-3} = \varphi'_1|B_{6k-1}\cap B'_{6k-3}\ ,\\
&\psi|B_{6k+2}\cap B'_{6k} = \varphi'_2|B_{6k+2}\cap B'_{6k}\ ,\\
&\psi|B_{6k}\cap B'_{6k-1} \quad \text{is an arbitrary pure state,}\\
&\psi|B_{6k-3}\cap B'_{6k-4} \quad \text{is an arbitrary pure state.}
\end{aligned}$$

□

Recall that τ is the gauge action of $\mathbf{T}$ on $\mathcal{O}_d$, i.e.,

$$\tau_z(s_i) = zs_i\ , \qquad z\in\mathbf{T}\ .$$

Let ε be the conditional expectation of $\mathcal{O}_d$ onto UHF_d defined by

$$\varepsilon(x) = \int_{\mathbf{T}} \tau_z(x)\frac{|dz|}{2\pi}\ , \qquad x\in\mathcal{O}_d\ .$$

Note that if φ is a gauge-invariant state of $\mathcal{O}_d$, then

$$\varphi = \varphi|_{\mathrm{UHF}_d}\circ\varepsilon\ .$$

Recall that λ is canonical endomorphism of $\mathcal{O}_d$: $\lambda(x) = \sum_{i=1}^{d} s_i x s_i^*$, $x\in\mathcal{O}_d$, and that the restriction of λ to UHF_d is the one-sided shift σ.

Lemma 4. *If φ is a gauge-invariant state on $\mathcal{O}_d$ then the following conditions are equivalent:*

(i) *φ is pure*

(ii) *$\varphi|_{\mathrm{UHF}_d}$ is pure and*
$\varphi|_{\mathrm{UHF}_d}\circ\sigma^n$ is disjoint from φ for $n = 1,2,\dots$

Proof. (i)⇒(ii). Since φ is pure, and gauge-invariant, it follows that $\varphi|_{\mathrm{UHF}_d}$ is pure. Let p be the support projection of φ in $\mathcal{O}_d^{**}$. Since p is minimal, and φ is gauge-invariant, it follows that for any $a\in\mathrm{UHF}_d$ and any multi-index $I = (i_1,i_2,\dots,i_n)$ with $|I| = n\ge 1$,

$$pas_Ip = \varphi(as_I)p = 0\ ,$$

where $s_I = s_{i_1}s_{i_2}\dots s_{i_n}$. Thus we obtain that

$$p(\mathrm{UHF}_d)\lambda^n(p) = 0\ ,$$

which implies that $\varphi|_{\mathrm{UHF}_d}\circ\sigma^n$ is disjoint from φ.

(ii)⇒(i). Let p be the support projection of $\varphi|_{\mathrm{UHF}_d}$ in $\mathrm{UHF}_d^{**}\subset\mathcal{O}_d^{**}$. It suffices to show that for any multi-indices I, J

$$ps_Is_J^*p\in\mathbf{C}p$$

since the linear span of $s_Is_J^*$ is dense in $\mathcal{O}_d$. If $|I|\ne[J|$, we have that $ps_Is_J^*p = 0$ by using the fact that $\varphi|_{\mathrm{UHF}_d}\circ\sigma^n$ is disjoint from φ for $n = \Big||I|-|J|\Big|$. If $[I| = |J|$, we have that $ps_Is_J^*p = \varphi(s_Is_J^*)p$ since $\varphi|_{\mathrm{UHF}_d}$ is pure. □

Lemma 5. *Let φ_1 and φ_2 be gauge-invariant pure states of $\mathcal{O}_d$ such that all $\varphi_i|_{\mathrm{UHF}_d}\circ\sigma^n$, $i = 1,2$, $n = 0,1,2,\dots$ are mutually disjoint. Then there exists an automorphism α of $\mathcal{O}_d$ such that $\alpha\circ\tau_z = \tau_z\circ\alpha$, $z\in\mathbf{T}$ and $\varphi_1 = \varphi_2\circ\alpha$.*

Proof. By Lemma 4, $\psi_1 = \varphi_1|_{\mathrm{UHF}_d}$ and $\psi_2 = \varphi_2|_{\mathrm{UHF}_d}$ are pure states on UHF_d. Applying Lemma 3 on ψ_1, ψ_2 in lieu of φ_1, φ_2, with $\varepsilon = 1$, we obtain pure states ψ_1', ψ_2' and ψ of UHF_d with the properties given there. Since ψ_i is equivalent to ψ_i', $\varphi_i' = \psi_i' \circ \varepsilon$ is a pure state of $\mathcal{O}_d$ by Lemma 4 and this state is equivalent to $\varphi_i = \psi_i \circ \varepsilon$. By Kadison's transitivity theorem we have a unitary $u \in \mathrm{UHF}_d$ such that $\psi_i' = \psi_i \circ \operatorname{Ad} u$; it follows that $\varphi_i' = \varphi_i \circ \operatorname{Ad} u$.

It is not automatical that ψ satisfies the condition that all $\psi \circ \sigma^n$, $n = 0, 1, 2, \dots$ are mutually disjoint and are disjoint from $\psi_i' \circ \sigma^n$. But using the freedom in constructing $\psi|_{B_{6k} \cap B_{6k-1}'}$ and $\psi|_{B_{6k-3} \cap B_{6k-4}'}$ successively, we can certainly impose this condition.

Thus we obtain three pure states ψ_1', ψ_2', ψ of UHF_d such that all $\psi_i' \circ \sigma^n$, $\psi \circ \sigma^n$ are mutually disjoint and ψ_i' and ψ are spotwise asymptotically equal as specified in Lemma 3. It now suffices to prove the lemma for the pairs $(\psi_1' \circ \varepsilon, \psi \circ \varepsilon)$ and $(\psi_2' \circ \varepsilon, \psi \circ \varepsilon)$. Thus replacing φ_1, φ_2 by one of these pairs, we may assume the lemma satisfy the additional condition that there exists an increasing sequence $\{k_n\}$ in $\mathbf{N}$ and an increasing sequence $\{B_n\}$ of finite type I subfactors of UHF_d such that

$$\begin{aligned}
&A_{k_1} \subset B_1 \subset A_{k_2} \subset B_2 \subset A_{k_3} \subset B_3 \subset \\
&\varphi_i|_{B_{3n+1}} \quad \text{is pure },\\
&\varphi_1|_{B_{3n+3} \cap B_{3n+1}'} = \varphi_2|_{B_{3n+3} \cap B_{3n+1}'} \quad \text{is pure}\\
&k_{3n+3} - k_{3n+2} \to \infty .
\end{aligned}$$

We shall construct a sequence $\{v_n\}$ of unitaries in UHF_d such that $\alpha = \lim_{n\to\infty} \operatorname{Ad}(v_n v_{n-1} \dots v_1)$ defines an automorphism of $\mathcal{O}_d$ with $\varphi_1 = \varphi_2 \circ \alpha$. To ensure the existence of the limit we choose the unitaries such that they mutually commute and $\sum \|\lambda(v_n) - v_n\| < \infty$. Since α commutes with the gauge action τ, this will complete the proof.

We fix a large $N \in \mathbf{N}$. We choose n_1 so large that the support projections $e_i^{(1)} = \operatorname{supp}(\varphi_i|_{B_{3n_1+1}})$ are almost orthogonal and $k_{3n_1+3} - k_{3n_1+2} > 2^{2(N+1)}$. Let w_1 be a partial isometry in B_{3n_1+1} with $w_1^* w_1 = e_1^{(1)}$, $w_1 w_1^* = e_2^{(1)}$. By the polar decomposition of the approximate unitary

$$w_1 + (1 - e_2^{(1)}) w_1^* (1 - e_1^{(1)}) + (1 - e_2^{(1)})(1 - e_1^{(1)}) ,$$

we obtain a unitary $v_1 \in B_{3n_1+1}$ such that

$$v_1 e_1^{(1)} = w_1 e_1^{(1)} = e_2^{(1)} w_1 = e_2^{(1)} v_1 \in B_{3n_1+1}$$

and $v_1(1 - e_2^{(1)})(1 - e_1^{(1)}) \approx (1 - e_2^{(1)})(1 - e_1^{(1)})$.

We next choose $n_2 > n_1$ so large that

$$\sigma^n \circ \operatorname{supp}(\varphi_i|_{B_{3n_2+1} \cap B_{3n_1+3}'}), \quad i = 1, 2, \ \ n = -2^{N-1}, -2^{-N+1}+1, \dots, 0, \dots, 2^{N+1}$$

are almost orthogonal and $k_{3n_2+2} - k_{3n_1+1} > 2^{2(N+2)}$. (Though σ is an endomorphism, σ^{-n} on $B_{3n_2+1} \cap B_{3n_1+3}'$ is well defined for $n = 1, 2, \dots, k_{3n_1+2}$.) Let w_2 be a partial isometry in $B_{3n_2+1} \cap B_{3n_2+3}'$ such that

$$w_2^* w_2 = e_1^{(2)} = \operatorname{supp}(\varphi_1|_{B_{3n_2+1} \cap B_{3n_1+3}'})$$

and

$$w_2 w_2^* = e_2^{(2)} = \operatorname{supp}(\varphi_2|_{B_{3n_2+1} \cap B_{3n_1+3}'}) ,$$

and let ζ be a partial isometry in $A_{k_{3n_2+2}+1} \cap A'_{k_{3n_1+3}}$ such that $\zeta^*\zeta = e_1^{(2)}$ and $\zeta\zeta^* = \sigma(e_1^{(2)})$.

Assume for the moment that $\sigma^\ell(e_i^{(2)})$, $i = 1, 2$; $\ell = -2^{N+1}, -2^{N+1}+1, \dots, 2^{N+1}$ are all orthogonal and set

$$e_{ij} = \begin{cases} \sigma^{i-1}(\zeta)\sigma^{i-2}(\zeta)\dots\sigma^j(\zeta) & i > j \\ \sigma^i(e_1^{(2)}) & i = j \\ \sigma^i(\zeta^*)\sigma^{i+1}(\zeta^*)\dots\sigma^{j-1}(\zeta^*) & i < j \end{cases}$$

for $i, j = -2^{-N+1}, \dots, 2^{N+1}$. Then (e_{ij}) is a family of matrix units such that $\sigma(e_{ij}) = e_{i+1,j+1}$ when $|i|, |i+1|, |j|, |j+1| \le 2^{N+1}$. Let

$$E = e_1^{(2)} + \sum_{\ell=1}^{2^{N+1}-1} (1 - e_1^{(2)}) \Big\{ \frac{2^{N+1} - \ell}{2^{N+1}} e_{\ell,\ell} + \frac{\ell}{2^{N+1}} e_{\ell-2^{N+1}, \ell-2^{N+1}}$$
$$+ \frac{1}{2^{N+1}} \sqrt{(2^{N+1} - \ell)\ell}\, (e_{\ell,\ell-2^{-N+1}} + e_{\ell-2^{-N+1},\ell}) \Big\} (1 - e_1^{(2)})$$

as in [Kis95]. Then E is a projection in $D_2 = A_{(k_{3n_2+2}+2^{N+1})} \cap A'_{(k_{3n_1+3}-2^{N+1})}$ and satisfies

$$\|\sigma(E) - E\| \sim \frac{1}{2^{\frac{N+1}{2}}} \ .$$

Let $w = w_2 + (1 - e_2^{(2)}) \Big(\sum_{\ell=1}^{2^{N+1}} (\sigma^\ell(w_2) + \sigma^{-\ell}(w_2)) \Big) (1 - e_1^{(2)})$ and

$$v = wE + (1 - F)w^*(1 - E) + (1 - F)(1 - E)$$

where $F = wEw^*$.

By the orthogonality assumption on $\sigma^\ell(e_i^{(2)})$, v is a unitary in D_2 and satisfies

$$\begin{aligned} &\|\sigma(v) - v\| \approx \|\sigma(E) - E\| \ , \\ &ve_1^{(2)} = w_2 e_1^{(2)} = e_2^{(2)} w_2 = e_2^{(2)} v \ . \end{aligned}$$

Note also that v commutes with v_1 and $e_i^{(1)}$.

Now, the projections $\sigma^\ell(e_i^{(2)})$, $i = 1, 2$, $\ell = -2^{N+1}, \dots, 2^{N+1}$ are not actually orthogonal but choosing n_2 so large that they are very close to being orthogonal, we may obtain a unitary v_2 in D_2 by polar decomposition of v such that v_2 satisfies the same conditions as above, i.e.,

$$\begin{aligned} &v_2 e_1^{(2)} = w_2 e_1^{(2)} = e_2^{(2)} w_2 = e_2^{(2)} v_2 \in B_{3n_2+1} \cap B'_{3n_1+3} \ , \\ &\|\lambda(v_2) - v_2\| \sim 2^{-\frac{N+1}{2}} \end{aligned}$$

and $v_2 \in D_2$.

Since

$$\begin{aligned} &\operatorname{supp}(\varphi_1|_{B_{3n_2+1}}) \\ &\quad = \operatorname{supp}(\varphi_1|_{B_{3n_1+1}}) \operatorname{supp}(\varphi_1|_{B_{3n_1+3} \cap B'_{3n_1+1}}) \operatorname{supp}(\varphi_1|_{B_{3n_2+1} \cap B'_{3n_1+3}}) \\ &\quad = e_1^{(1)} p e_1^{(2)} \end{aligned}$$

with $p = \mathrm{supp}(\varphi_1|_{B_{3n_1+3}\cap B'_{3n_1+1}}) = \mathrm{supp}(\varphi_2|_{B_{3n_1+3}\cap B'_{3n_1+1}})$, and since the operators $v_1e_1^{(1)} = e_2^{(1)}v_1, p$, and $v_2e_1^{(2)} = e_2^{(2)}v_2$ commute, we obtain that

$$\begin{aligned} v_1v_2 \cdot \mathrm{supp}(\varphi_1|_{B_{3n_2+1}}) &= v_1v_2e_1^{(1)}pe_1^{(2)} \\ &= v_1e_1^{(1)}v_2e_1^{(2)}p \\ &= e_2^{(1)}v_1e_2^{(2)}v_2p \\ &= pe_2^{(1)}e_2^{(2)}v_1v_2 = \mathrm{supp}(\varphi_2|_{B_{3n_2+1}})v_1v_2 \ . \end{aligned}$$

Here we have also used the fact that v_1 commutes with $e_2^{(2)}$. We repeat this procedure. Thus we obtain an increasing sequence $\{n_k\}$ in $\mathbf{N}$ and a sequence $\{v_k\}$ of mutually commuting unitaries such that

$$\begin{aligned} &\|\lambda(v_k) - v_k\| \sim 2^{-\frac{N+k}{2}} \ , \\ &v_ke_1^{(k)} = e_2^{(k)}v_k \in \mathcal{B}_{3n_k+1} \cap \mathcal{B}'_{3n_{k-1}+3} \end{aligned}$$

where

$$e_i^{(k)} = \mathrm{supp}(\varphi_i|_{\mathcal{B}_{3n_k+1}\cap\mathcal{B}'_{3n_{k-1}+3}}) \ ,$$

and such that $\mathrm{Ad}(v_k \dots v_1)$ maps $\mathrm{supp}(\varphi_1|_{\mathcal{B}_{3n_k+1}})$ into $\mathrm{supp}(\varphi_2|_{\mathcal{B}_{3n_k+1}})$. Then the limit $\alpha = \lim_k \mathrm{Ad}(v_k \dots v_1)$ defines the desired automorphism. □

Theorem 6. *Let φ_1 and φ_2 be gauge-invariant pure states of $\mathcal{O}_d$. Then there exists an automorphism α of $\mathcal{O}_d$ such that $\varphi_1 = \varphi_2 \circ \alpha$.*

Proof. If φ_1 is disjoint from φ_2, then it follows that $(\varphi_i|_{\mathrm{UHF}_d}) \circ \sigma^n = \varphi_i \circ \lambda^n|_{\mathrm{UHF}_d}$, $i = 1, 2$, $n = 0, 1, 2, \dots$ are mutually disjoint (by Lemma 4); thus the assertion follows from Lemma 5. If φ_1 is equivalent to φ_2, there is a unitary $u \in \mathcal{O}_d$ such that $\varphi_1 = \varphi_2 \,\mathrm{Ad}\, u$ (by Kadison's transitivity). □

3. Pure states mapped into Cuntz states by endomorphisms

There is a one-to-one correspondence between the set $\mathcal{U}(\mathcal{O}_d)$ of unitaries of $\mathcal{O}_d$ and the set $\mathrm{End}(\mathcal{O}_d)$ of unital endomorphisms of $\mathcal{O}_d$; if $u \in \mathcal{U}(\mathcal{O}_d)$, the endomorphism α_u is defined by $\alpha_u(s_i) = us_i$ and if $\alpha \in \mathrm{End}(\mathcal{O}_d)$, α corresponds to the unitary u defined by $u = \sum_{i=1}^{d} \alpha(s_i)s_i^*$. Define

$$\begin{aligned} \mathcal{U}_i &= \{u \in \mathcal{U}(\mathcal{O}_d) | \quad \alpha_u \text{ is an inner automorphism}\} \\ \mathcal{U}_a &= \{u \in \mathcal{U}(\mathcal{O}_d) | \quad \alpha_u \text{ is an automorphism}\} \\ \mathcal{U}_s &= \mathcal{U}(\mathcal{O}_d) \setminus \mathcal{U}_a \ . \end{aligned}$$

Proposition 7. *Let $\mathcal{U}_i, \mathcal{U}_a, \mathcal{U}_s$ be as above.*
(i) $\mathcal{U}_i$ is a dense subset of $\mathcal{U}(\mathcal{O}_d)$.
(ii) $\mathcal{U}_a$ is a dense G_δ subset of $\mathcal{U}(\mathcal{O}_d)$.
(iii) $\mathcal{U}_s$ is a dense F_σ subset of $\mathcal{U}(\mathcal{O}_d)$.

Proof. M. Rørdam proved (i) in [Rør93] and the other statements are more or less known.

We shall give a proof of (i). We again denote by λ the canonical endomorphism of $\mathcal{O}_d : \lambda(x) = \sum_{i=1}^{d} s_ixs_i^*$, $x \in \mathcal{O}_d$. Since the unitary corresponding to $\mathrm{Ad}\, v$ is $v\lambda(v^*)$, it suffices to show that $v\lambda(v^*)$, $v \in \mathcal{U}(\mathcal{O}_d)$, is dense in $\mathcal{U}(\mathcal{O}_d)$. If UHF_d denotes the C*-subalgebra generated by $s_{i_1}s_{i_2}\dots s_{i_n}s_{j_n}^*\dots s_{j_1}^*$, then we mentioned in the introduction that UHF_d is isomorphic to the UHF algebra $\bigotimes_{\mathbf{N}} M_d$ and $\lambda|\mathrm{UHF}_d$ corresponds to the one-sided shift on $\bigotimes_{\mathbf{N}} M_d$. Thus $\lambda|\mathrm{UHF}_d$ satisfies the Rohlin property, [BKRS93], [Kis95]. In particular for any n and $\varepsilon > 0$ there is an orthogonal family $e_0, e_1, \dots, e_{n-1}$ of projections in UHF_d such that

$$\sum_{i=0}^{d^n-1} e_i = 1$$
$$\|\lambda(e_i) - e_{i+1}\| < \varepsilon$$

with $e_{d^n} = e_0$. The similar properties hold for $\mathrm{Ad}\,u \circ \lambda$, i.e., if UHF_d^u denotes the C*-subalgebra generated by $us_{i_1}us_{i_2}\dots us_{i_n}s_{j_n}^*u^*\dots s_{j_1}^*u^*$, then $\mathrm{Ad}\,u \circ \lambda|\mathrm{UHF}_d^u$ corresponds to the one-sided shift on $\bigotimes_{\mathbf{N}} M_d$. Hence for any n and $\varepsilon > 0$ there is an orthogonal family $f_0, f_1, \dots, f_{d^n-1}$ of projections in UHF_d^u such that

$$\sum_{i=0}^{d^n-1} f_i = 1$$
$$\|\,\mathrm{Ad}\,u \circ \lambda(f_i) - f_{i+1}\| < \varepsilon$$

with $f_{d^n} = f_0$. Suppose we have chosen such projections e_i, f_i for the same n. Since $K_0(\mathcal{O}_d) = \mathbf{Z}/(d-1)\mathbf{Z}$, we have that $[e_0] = 1 = [f_0]$ in $K_0(\mathcal{O}_d)$ and so obtain a partial isometry $w \in \mathcal{O}_d$ such that $w^*w = e_0$, $ww^* = f_0$. We find unitaries $v_1, v_2 \in \mathcal{O}_d$ such that $\mathrm{Ad}\,v_1\lambda(e_i) = e_{i+1}$, $\mathrm{Ad}\,v_2\,\mathrm{Ad}\,u\lambda(f_i) = f_{i+1}$, and $\|v_1 - 1\| \approx 0$, $\|v_2 - 1\| \approx 0$ (depending on ε). Let

$$z = w^*(L_{v_2u}R_{v_1^*}\lambda)^{d^n}(w)$$

where $R_{v_1^*}$ is the right multiplication by v_1^* and L_{v_2u} is the left multiplication by v_2u. Since $(L_{v_2u}R_{v_i^*}\lambda)^i(w)$ is a partial isometry with initial projection e_i and final projection f_i, z is a unitary in $e_0\mathcal{O}_de_0$. Since $K_1(\mathcal{O}_d) = 0$ and $\mathcal{O}_d$ has real rank zero, we find a sequence $z_0, z_1, \dots, z_{d^n-1}$ of unitaries in $e_0\mathcal{O}_de_0$ such that $z_0 = z$, $z_{d^n-1} = 1$,

$$\|z_i - z_{i+1}\| < 4/d^n\ .$$

Define a unitary v by

$$v = \sum_{i=0}^{d^n-1} (L_{v_2u}R_{v_1^*}\lambda)^i(wz_i)$$

Then since

$$\begin{aligned} &v - (L_{v_2u}R_{v_1^*}\lambda)(v) \\ &\quad= \sum_{i=1}^{d^n-1} (L_{v_2u}R_{v_1^*}\lambda)^i(wz_i - wz_{i-1}) + wz_0 - (L_{v_2u}R_{v_1^*}\lambda)^{d^n}(w)\ , \end{aligned}$$

it follows that

$$\|v - L_{v_2u}R_{v_1^*}\lambda(v)\| < 4/d^n$$

or

$$\|v - u\lambda(v)\| \ .\ 4/d^n\ .$$

This completes the proof of (i).

Since $\mathcal{U}_a \supset \mathcal{U}_i$, $\mathcal{U}_a$ is dense. That $\mathcal{U}_a$ is a G_δ set follows from

$$\mathcal{U}_a = \bigcap_n \bigcap_j \bigcup_i \left\{ u \in \mathcal{U}(\mathcal{O}_d); \|\alpha_u(x_i) - x_j\| < \frac{1}{n} \right\}$$

where $\{x_i\}$ is a dense sequence in $\mathcal{O}_d$.

If $\mathcal{U}_a$ contains a non-empty open set, then it follows that $\mathcal{U}_a = \mathcal{U}(\mathcal{O}_d)$ or $\mathcal{U}_s = \emptyset$. Because for any unitaries u, w of $\mathcal{O}_d$ we find a unitary v such that $w\lambda(v) \approx vu$. (Apply the previous argument for the endomorphism $\operatorname{Ad} u \circ \lambda$ instead of λ and the unitary wu^*.) Since $v\mathcal{U}_a\lambda(v^*) = \mathcal{U}_a$ for any unitary $v \in \mathcal{O}_d$, the above fact implies that $\mathcal{U}_a$ contains an arbitrary unitary. But we know that $\mathcal{U}_s \neq \emptyset$. For example if $u = \sum s_i s_j s_i^* s_j^*$, then $\alpha_u = \lambda$ and $\lambda(\mathcal{O}_d)' \simeq M_d$. Thus we obtain that $\mathcal{U}_s$ is dense. □

For a unit vector $\xi \in \mathbf{C}^d$ we have defined the Cuntz state f_ξ of $\mathcal{O}_d$ by

$$f_\xi(s_{i_1} \dots s_{i_m} s_{j_n}^* \dots s_{j_1}^*) = \xi_{i_1} \dots \xi_{i_m} \overline{\xi_{j_n}} \dots \overline{\xi_{j_1}}$$

It follows that f_ξ is a unique pure state of $\mathcal{O}_d$ satisfying

$$f_\xi \left(\sum_{i=1}^d \overline{\xi_i} s_i \right) = 1 \ .$$

Let F be the linear span of $s_i s_j^*$, $i, j = 1, \dots, d$. Then F is isomorphic to M_d and each unitary u in F defines an automorphism α_u of $\mathcal{O}_d$. This group of automorphisms acts transitively on the compact set of Cuntz states.

We denote by f_0 the Cuntz state f_ξ with $\xi = (1, 0, \dots, 0)$.

Proposition 8. *If φ is a pure state of $\mathcal{O}_d$, there is a unital endomorphism α of $\mathcal{O}_d$ such that $\varphi \circ \alpha = f_0$, where f_0 is the Cuntz state defined above. Furthermore α may be chosen so that $\pi_\varphi \circ \alpha(\mathcal{O}_d)''$ contains the one-dimensional projection onto $\mathbf{C}\Omega_\varphi$.*

Proof. It suffices to show that if φ is a pure state there is a unitary $u \in \mathcal{O}_d$ such that

$$\varphi(us_1) = 1 \ .$$

Since $\mathcal{O}_d$ has real rank zero, there is a decreasing sequence (e_n) of projections in $\mathcal{O}_d$ such that φ is the unique state satisfying $\varphi(e_n) = 1$ for $n = 1, 2, \dots$, i.e., (e_n) converges to the support projection of φ in $\mathcal{O}_d^{**}$. We may further assume that $[e_n] = 0$ in $K_0(\mathcal{O}_d)$.

Pick up a projection $e = e_n$ such that $\varphi(e) = 1$ and $e < 1$. Then es_1^* is a partial isometry with initial projection $s_1 e s_1^*$ and final projection e. Let w be a partial isometry such that $w^*w = 1 - s_1 e s_1^*$ and $ww^* = 1 - e$. Then $u = es_1^* + w$ is a unitary in $\mathcal{O}_d$ such that

$$us_1 e = (es_1^* + w)s_1 e = e \ .$$

Thus we have that $\varphi(us_1) = 1$.

To prove the last statement we shall modify u so that φ is the unique state satisfying

$$\varphi(us_1) = 1 \ .$$

We have chosen $e = e_n$. We let

$$h = \sum_{k=1}^\infty 2^{-k} e_{n+k} \ .$$

Then h is self-adjoint with $0 \leq h \leq 1$ and φ is the only state satisfying $\varphi(h) = 1$. Let

$$u_1 = e^{2\pi i h} u \ .$$

Then $u_1 s_1 e = e^{2\pi i h} e$ and the assertion follows. $\square$

References

[BJ97] O. Bratteli and P.E.T. Jorgensen, Endomorphisms of $\mathcal{B}(\mathcal{H})$, II, *J. Funct. Anal.* **145** (1997), 323–373.

[BJP96] O. Bratteli, P.E.T. Jorgensen and G. Price, Endomorphisms of $\mathcal{B}(\mathcal{H})$, in W. Arveson et al., eds., "Quantization of Nonlinear Partial Differential Equations", Amer. Math. Soc. 1996.

[BJKW] O. Bratteli, P.E.T. Jorgensen, A. Kishimoto and R.F. Werner, Pure states on $\mathcal{O}_d$, J. Operator Theory, to appear.

[BK99] O. Bratteli and A. Kishimoto, Trace scaling automorphisms of certain stable AF algebras II, preprint 1999.

[BKRS93] O. Bratteli, A.K. Kishimoto, M. Rørdam and E. Størmer, The crossed product of a UHF algebra by a shift, *Ergodic Theory and Dyn. Sys.* **13** (1993), 615–626.

[Bra72] O. Bratteli, Inductive limits of finite dimensional C*-algebras, *Trans, Amer. Math. Soc.* **171** (1972), 195–234.

[Cun77] J. Cuntz, Simple C*-algebras generated by isometries, *Comm. Math. Phys.* **57** (1977), 173–185.

[Eva80] D.E. Evans, On $\mathcal{O}_n$, *Publ. RIMS. Kyoto Univ.* **16** (1980), 915–927.

[Kis95] A. Kishimoto, The Rohlin property for automorphisms of UHF algebras, *J. reine argew. Math.* **465** (1995), 183–196.

[KR86] R.V. Kadison and J.R. Ringrose, Fundamentals of the theory of operator algebras, Volume II, Academic Press 1986.

[KT78] A. Kishimoto and H. Takai, Some remarks on C*-dynamical systems with a compact abelian group, *Publ. Res. Inst. Math. Sci.* **14** (1978), 388–397.

[Pow67] R.T. Powers, Representations of uniformly hyperfinite algebras and their associated von Neumann rings, *Ann. of Math.* **86** (1967), 138–171.

[Rør93] M. Rørdam, Classification of inductive limits of Cuntz algebras, *J. reine angew. Math.* **440** (1993), 175–200.

Mathematics Institute, University of Oslo, PB 1053 Blindern, N-0316 Oslo, Norway

Department of Mathematics, Hokkaido University, Sapporo, 060 Japan